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APPLICATION OF STRAINRANGE PARTITIONING TO THE PREDICTION OF MPC CREEP-FATIGUE DATA FOR 2 1/4 Cr-1Mo STEEL

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APPLICATION OF STRAINRANGE PARTITIONING TO THE PREDICTION OF MPC CREEP-FATIGUE DATA FOR 2 1/4 Cr-1Mo STEEL

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ABSTRACT

Strainrange Partitioning is used to predict the long-time cyclic lives of The Metal Properties Council(MPC) "creep-fatigue interspersion" and "cyclic creep-rupture" tests conducted with annealed 2 1/4Cr-1Mo steel. Observed lives agree with predicted lives within factors of two. The Strainrange Partitioning life relations used for the long-time predictions were established from short-time creep-fatigue data generated at NASA-Lewis on the same heat of material.

NOMENCLATURE

F_{PP} = $\Delta\varepsilon_{PP}/\Delta\varepsilon_{IN}$

F_{CP} = $\Delta\varepsilon_{CP}/\Delta\varepsilon_{IN}$

NOBS = observed number of combined creep-fatigue cycles to failure

NPRE = predicted number of combined creep-fatigue cycles to failure

n = number of rapid fatigue cycles per creep period

N_{PP} = pure PP life, cycles to failure

N_{CP} = pure CP life, cycles to failure

$\Delta\varepsilon_{IN}$ = inelastic strainrange

$\Delta\varepsilon_{PP}$ = PP component of inelastic strainrange

$\Delta\varepsilon_{CC}$ = CC component of inelastic strainrange

$\Delta\varepsilon_{CP}$ = CP component of inelastic strainrange

$\Delta\varepsilon_{PC}$ = PC component of inelastic strainrange

INTRODUCTION

The method of Strainrange Partitioning, a strain based approach for dealing with high-temperature, low-cycle fatigue, was proposed in 1971 by Manson, Halford, and Hirschberg (1)*. In the intervening five years, considerable experience with the use of the method in laboratory investigations has developed confidence in the engineering utility of the concept. Studies have produced refinements to the basic approach [Manson (2), Halford, Hirschberg, and Manson (3), and Manson, Halford, and Nachtigall (4)], extensions to broader ranges of applicability [Halford and Manson (5), Zamrik (6), and Manson and Halford (7)] concise characterizations of the creep-fatigue properties of a wide range of engineering alloys [Leven (8), Annis, VanWanderham, and Wallace (9), Kortovich (10), and Sheffler (11,12)], and have shown prediction capabilities of the method for short-time results [Saltsman and Halford (13) for AISI Types 304 and 316 stainless steel, Brinkman, et al. (14) and Ellis, et al. (15) for annealed 2 1/4Cr-1Mo steel].

The purpose of this paper is to demonstrate the applicability of the method to the prediction of long-time (500-5000 hr) creep-fatigue results on the basis of short-time (0.1-100 hr) material characterization tests.

This is an extremely important consideration in the design

* Numbers in parentheses designate references at end of text.

of engineering structures which are to experience service lifetimes that are well in excess of the lifetimes attainable in laboratory material characterization tests.

Cyclic life predictions are made for the "creep-fatigue interspersion" and "cyclic creep rupture" tests conducted with annealed 2 1/4Cr-1Mo steel by the Materials Technology Corporation for The Metal Properties Council (MPC). Curran and Wundt have described the MPC program and discussed all results to date in (16). The program was designed to generate relatively long-time laboratory data for the specific purpose of assessing the validity of the time-fraction and cycle-fraction approach to high-temperature, creep-fatigue interaction as used in ASME Code Case 1592. Even though the results were obtained in a manner best suited for evaluation of the time-fraction and cycle-fraction approach, interpretation in terms of Strainrange Partitioning was also possible as is demonstrated in this paper.

The MPC tests were conducted in air at 1000 deg F (538 deg C) and involved interspersion of rapid strain cycles (0 to 22 cycles) between constant tensile stress-hold periods (23 or 47 hours). The induced tensile creep was always rapidly reversed to zero by compressive plasticity so that ratchet strains did not occur. The interspersed rapid strain cycles were then applied. Figure 1 illustrates the stress-strain cycles involved.

Life predictions were made using the strainrange-life

relations obtained from short-time material characterization tests conducted at the NASA-Lewis Research Center (1 and 3) using tubular specimens (17) taken from the same extruded and annealed thick-walled steel pipe as the MPC specimens. We would like to acknowledge Mr. A. O. Schaeffer of the Metal Properties Council for providing the material for this program.

REVIEW

Procedures are described in detail in a recent paper by Hirschberg and Halford (18) for characterizing the creep-fatigue behavior of metallic materials and applying the resultant strainrange-life relations to predicting lives of independently conducted laboratory tests. Only a brief summary of the method is provided herein.

The method has its origin rooted in basic concepts: in any axial hysteresis loop there are two directions of straining, tension and compression, and there are two basic types of inelastic strain, "plasticity" (time-independent strain), and "creep" (time-dependent strain); and creep-fatigue life in a given environment is controlled primarily by the ability of a material to absorb cyclic inelastic strain.

By combining the two directions of axial strain with the two types of inelastic strain, a hysteresis loop of width $\Delta\varepsilon_{IN}$ can be partitioned into the four basic strainranges:

$$\Delta\varepsilon_{IN} = \Delta\varepsilon_{PP} + \Delta\varepsilon_{CC} + \Delta\varepsilon_{CP} \text{ (or } \Delta\varepsilon_{PC})$$

The relationship between strainrange and cyclic life can be expressed by an equation similar to the Manson-Coffin equation. These life relations are established by conducting completely reversed, strain-cycling, creep-fatigue tests as described in (18).

In principle, in any high-temperature, completely-reversed, strain cycle, the inelastic strainrange can be partitioned into its above defined components. Then, knowing these components, the cyclic life can be predicted using the interaction damage rule (2) and the characteristic life relations obtained from independent laboratory tests.

ANALYSIS

Establishment of Life Relations

The strainrange-life relations used for the life predictions are based on tests conducted at the NASA-Lewis Research Center. Hour-glass tubular test specimens (17) were machined from the same extruded and annealed steel pipe as the uniform gage length, solid specimens used in the MPC program. Isothermal test temperatures ranged from 950 to 1200 deg F (510 to 648 deg C), and all tests were performed with fully-reversed strain limits. Although the results of most of these tests have been published in earlier reports (1 and 3), for convenience they are also listed in Table 1. Only the PP and CP results are presented since they are the only data needed to analyze the MPC results.

The two life relations obtained from these data using the interaction damage rule are shown in Figs. 2a and 2b and are expressed in the form of the Manson-Coffin equation relating strainrange and cyclic life. The insensitivity of the life relations to temperature for this material is shown in (3).

The best values for the two constants in each life relation (exponent and intercept) were obtained from a linear least squares curve fit of the data. The inelastic strainrange is the independent variable and is assumed to be known without error. The life relations are put in linear form by taking logarithms of strainrange and cyclic life. The correlation coefficient and standard error of estimate were also determined for each life relation using the methods given in (13).

Comparison of the PP and CP life relations reveals a life difference at an inelastic strainrange of 1 percent, for example, of a factor of only 2.6. This is in sharp contrast to the behavior of alloys such as the austenitic stainless steels which exhibit, typically, a factor of 10 to 20 or more difference between PP and CP lives for a 1 percent inelastic strainrange. These differences are attributable to the fact that the 2 1/4Cr-1Mo steel does not exhibit intergranular void growth and cracking during tensile creep, whereas the austenitic steels do (1).

Partitioning of MPC Test Data

The analysis of the MPC tests was made using the detailed test results made available to the authors by The Metal Properties Council through the efforts of Mr. R. M. Curran and Mr. B. Wundt. The analyzed tests listed in Table 2 include (except for duplicates) those reported by Curran and Wundt (16) for annealed 2 1/4Cr-1Mo steel.

In the interspersion tests, one combined cycle (Fig. 1) consists of a creep period (23 or 47 hours) at a constant tensile load followed by a rapid reversal of strain back to zero, plus a specified number of interspersed rapid fatigue cycles at a fixed total strain range with zero mean strain. At the beginning and end of each combined cycle, the accumulated strain is forced to be nominally zero. It should be noted that the number of interspersion fatigue cycles reported in (16) for the MPC tests includes an "extra" half-cycle which is accounted for in the strainrange partitioning analysis as being the half-cycle that is used to reverse the tensile creep strain. It is to be emphasized that all portions of the inelastic strain in the MPC tests are taken into account in the strainrange partitioning analysis.

Partitioning the hysteresis loop for the creep period is a straight-forward procedure. The inelastic strainrange is given by the width of the hysteresis loop (Fig. 1), and the CP component is simply the amount of strain accumulated during the

creep period at constant stress. The PP component is the difference between the inelastic strainrange and the CP component.

The hysteresis loop during the interspersed fatigue cycling is also shown in Fig. 1. It is assumed herein that the straining rate during rapid cycling is rapid enough to preclude creep. Hence, all of the inelastic strain during rapid cycling is taken to be of the PP type. The values for this PP strain component are given in the detailed test results.

During the creep portion of these tests, the stress level and stress hold-time were the controlled parameters. This resulted in a possible variation in the inelastic strainrange and its components from period to period. Thus, to account for any variation in behavior, the inelastic strainrange for each cycle was partitioned for every test.

In partitioning the data used in this report, all time-independent strain was regarded as "plasticity" and all time-dependent strain was regarded as "creep" as originally recommended (1). A recent study (4) indicates that more accurate life predictions are possible if only the steady state creep strain is regarded as "creep". However, it was not possible to apply this new concept here, since stress hold-times for the characterization tests used in establishing the life relations were of insufficient duration to establish reliable steady-state

creep rates.

Life Prediction

Cyclic life predictions were made for the tests listed in Table 2. The predictions are based on the life relations shown in Figs. 2a and 2b and the interaction damage rule (2). Note that when these tests are analyzed by the method of Strainrange Partitioning, the number of rapid cycles per combined cycle is 1/2 cycle less than specified in (16) for reasons discussed earlier.

Since the MPC tests are stress controlled and not strain controlled during the creeping period, the inelastic strainrange (and its PP and CP components) is free to vary as its instantaneous mechanical properties dictate. Slight variations in load and temperature could also cause these variations.

Examples of the extremes in behavior are shown in Figs. 3a and 3b. In test bar 2A5AA (Fig. 3a), the inelastic strainrange varied little over most of its life. The material cyclically strain softened slightly, but reached saturation by the third creep period. The inelastic strainrange then remained essentially constant over most of the test life. In Fig. 3b, the inelastic strainrange for test bar 2A6BB peaked at the second creep period and then varied between 1.2 and 1.4 percent over most of the test.

Because of these variations, life predictions were made in two ways. The first was by partitioning the hysteresis loops for each creep period and summing the resultant fractions for each cycle. This is a tedious process. The inelastic strainrange during rapid cycling showed little variation, so the average reported values were used in determining this damaging component.

The second set of life predictions was made by simply partitioning the hysteresis loop for the creep period at half the observed life and assuming that these values were constant over the observed life of the test. The inelastic strainrange during rapid cycling was also taken at half the observed life.

An example calculation of life using the half-life strainranges for test bar 2A5AA is given in the Appendix.

The method of analysis was programmed for a digital computer and automatic computer plots were made of the results.

COMPARISON OF PREDICTED AND OBSERVED LIVES

The results of the two sets of life prediction calculations for the interspersion creep-fatigue and cyclic creep rupture tests are shown in Figs. 4a and 4b where observed life is plotted versus predicted life. These results are also given in Table 3.

In Fig. 4a, the lives were predicted by summing the damage on a combined cycle-by-combined cycle basis; in Fig. 4b, the lives were predicted by simply using the partitioned strainrange

values at half-life. In these figures, the central line represents exact agreement between observed and predicted lives, whereas the dashed lines on either side represent factors of two in life between observed and predicted values.

An examination of Fig. 4a shows that the points are essentially equally divided about the central line. Five points are to the right of and above the central line (i.e. NOBS/NPRE < 1.0), five points are to the left of the line (NOB/NPRE > 1.0), and one point is exactly on the line (NOB = NPRE). All points lie within the dashed lines representing factors of two agreement. In Fig. 4b, nine points are to the right of and above the central line, while only two points are to the left and below this exact agreement line. Accuracy of life predictions made by either way is considered to be highly satisfactory.

Life predictions of reasonable accuracy can be made using only the partitioned strainrange values at half-life since the amount of creep strain per cycle remained reasonably constant over the majority of the observed life. Hence the half-life cycle is representative of the "average" cycle.

Table 4 gives the damage fractions for the life predictions using the partitioned strainrange values at half-life. An examination of Table 4 shows that in the interspersion creep-fatigue tests the damage varies from being predominantly the PP type incurred during rapid cycling (test bars 2A2B, 2A6BB,

2A3AA, 2A5AA, 2B1A, and 2B3A) to predominantly CP type incurred during the creep period (test bars 2A4B, 2A1A, and 2A4E). The major damage in the two cyclic creep rupture tests is of the CP type.

The important point to note with regard to the results of this investigation is that the exposure times for the MPC and the characterization tests are vastly different. The MPC tests lasted from about 500 to 5000 hours, while the characterization tests lasted no more than about 100 hours for the CP tests and were as short as 0.1 hours for the PP tests. It should be pointed out, however, that annealed 2 1/4 Cr-1Mo steel does not undergo intergranular cracking due to creep deformation in the temperature-time range of either the characterization or MPC tests (1 and 16). For other alloys, such as austenitic stainless steel, which are susceptible to grain boundary void growth and sliding during creep deformation, such extrapolation may be risky if the short-time behavior does not reflect the same mechanisms of damage as the long-time behavior.

SUMMARY OF RESULTS

The following results were obtained from a study to predict the cyclic lives of the MPC creep-fatigue interspersion and cyclic creep rupture tests at 1000 deg F (538 deg C) on specimens of extruded and annealed 2 1/4 Cr-1Mo steel using the method of Strainrange Partitioning:

1. By partitioning the creep and plastic strains within every cycle and summing the damge on a cycle-by-cycle basis, the predicted lives agree with the observed lives within factors of two. In order to greatly simplify the calculations, only the strains for the combined cycle at half the observed life were partitioned and predictions made using these values. These predicted lives also agreed with the observed lives within factors of two.

2. The life relations used in these predictions are based on tests which lasted from about 0.1 to 100 hours, while the MPC tests lasted from about 500 to 5000 hours. Despite this large difference in testing times, agreement between predictions and observations was excellent.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 3, 1976

APPENDIX

Example Life Calculation Using Half-Life Strainrange Values For Test Bar 2A5AA

The predicted number of combined creep-fatigue cycles to failure (NPRE) is determined by the following equation which is based on the interaction damage rule modified to include the damage due to the interspersed rapid fatigue cycling.

$$\underbrace{\frac{F_{CP}}{N_{CP}} + \frac{F_{PP}}{N_{PP}}}_{\text{Creep portion}} + \underbrace{\frac{n}{N_{PP}}}_{\substack{\text{Interspersed}\\ \text{fatigue portion}}} = \frac{1}{NPRE}$$

The partitioned strainrange values for the creep portion and the interspersed fatigue portion of the combined cycle at the observed half-life are as follows.

<u>Creep Portion</u>

$\Delta\varepsilon_{PP}$	= 0.00095	F_{PP}	$= \Delta\varepsilon_{PP}/\Delta\varepsilon_{IN}$	= 0.074
$\Delta\varepsilon_{CP}$	= 0.01192	F_{CP}	$= \Delta\varepsilon_{CP}/\Delta\varepsilon_{IN}$	= 0.926
$\Delta\varepsilon_{IN}$	= 0.01287			1.000

<u>Interspersed Fatigue Portion</u>

$\Delta\varepsilon_{PP}$ = 0.0120

The number of interspersed fatigue cycles (n) per creep period from Table 2 is 22.

The PP and CP life for the creep portion and the PP life for the interspersed fatigue portion of the combined cycle are determined using the life relations given in Figs. 2a and 2b. Note that when determining the life for a specific strainrange component, the entire inelastic strainrange is considered to be of that type (2).

Creep Portion

$$N_{CP} = \left(\frac{0.233}{0.01287}\right)^{1/0.515} = 277 \text{ cycles}$$

$$N_{PP} = \left(\frac{0.559}{0.01287}\right)^{1/0.570} = 747 \text{ cycles}$$

Interspersed Fatigue Portion

$$N_{PP} = \left(\frac{0.559}{0.0120}\right)^{1/0.570} = 845 \text{ cycles}$$

The number of combined creep-fatigue cycles to failure (NPRE) can now be calculated.

$$\frac{0.926}{277} + \frac{0.074}{747} + \frac{22}{845} = \frac{1}{NPRE}$$

Thus NPRE = 34 cycles. This compares well with the observed life (NOBS) of 29 cycles.

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TABLE 1. - STRAINRANGE PARTITIONING DATA FOR ANNEALED $2\frac{1}{4}$ Cr-1Mo

STEEL. NASA RESULTS USED TO ESTABLISH

LIFE RELATIONS. REFS 1 AND 2

Specimen number	Temperature		Total strain range, percent	Inelastic strain range, percent	PP strain range, percent	CP strain range, percent	Cycles to failure	Time to failure, hr
	°F	°C						
64	1100	593	3.40	2.97	2.97	----	186	0.3
62	1100	593	3.73	3.36	3.36	-----	192	1.8
41	950	510	2.42	1.99	1.99	-----	267	.1
53	1050	565	1.54	1.20	1.20	-----	941	.3
49	1100	593	1.09	.77	.77	-----	1 285	.6
15	1200	648	.85	.57	.57	-----	3 234	1.0
27	1100	593	.70	.41	.41	-----	4 116	1.9
31	1100	593	.44	.20	.20	-----	13 359	4.6
35	1100	593	.47	.23	.23	-----	25 360	30.4
47	1050	565	.35	.13	.13	-----	55 211	30.7
26	950	510	2.80	2.36	.89	1.47	88	66.3
39	1100	593	1.64	1.34	.50	.84	449	21.0
2	1100	593	1.04	.78	.35	.43	1 337	23.4
25	1200	648	.71	.49	.22	.27	1 350	17.0
10	1200	648	.76	.56	.25	.31	1 950	104.0
29	1100	593	.56	.33	.15	.18	5 734	99.2

TABLE 2. - MPC CREEP-FATIGUE INTERSPERSION AND CYCLIC CREEP RUPTURE RESULTS FOR $2\frac{1}{2}$Cr-1Mo STEEL AT 1000° F (538° C)

Test bar	Creep stress		Monotonic rupture, time, hr	Duration of creep stress per combined cycle, hr	Total strain range, percent	Number of[a] interspersed fatigue cycles	Observed life, number of combined cycles	Test time, hr
	ksi	MPa						
2A4B	22.5	326	1000	47	2.3	1	59	2776
2A1A	22.5	326	1000	23	1.5	1	141	3243
2A2B	22.5	326	1000	23	2.3	2	73	1691
2A3AA	22.5	326	1000	23	1.5	5	96	2186
2A6BB	22.5	326	1000	23	2.3	11	39	914
2A5AA	22.5	326	1000	23	1.5	22	29	667
2A4E	22.5	326	1000	47	.55	1	67	3179
2B1A	19.5	283	3000	23	1.5	1	202	4664
2B3A	19.5	283	3000	23	1.5	5	92	2135
2AOO	22.5	326	1000	23	---	--	99	2281
2BOO	19.5	283	3000	23	---	--	241	5549

[a]Number of PP type interspersion fatigue cycles used in damage analysis by method of strainrange partitioning is 1/2 cycle less than used by MPC since 1/2 cycle is used to plastically reverse the 1/2 cycle of tensile creep in each combined cycle.

TABLE 3. - COMPARISON OF PREDICTED AND OBSERVED CYCLIC LIVES OF MPC TESTS

Test bar	Observed life cycles	Predicted cyclic life		Life ratio: observed/predicted	
		Damage summed every cycle	Damage based on half life cycle	Damage summed every cycle	Damage based on half life cycle
2A4B	59	46	57	1.28	1.04
2A1A	141	139	160	1.01	.88
2A2B	73	89	122	.82	.60
2A3AA	96	88	99	1.09	.97
2A6BB	39	30	30	1.30	1.30
2A5AA	29	30	34	.97	.85
2A4E	67	53	68	1.26	.99
2B1A	202	346	408	.58	.50
2B3A	92	139	153	.66	.60
2AOO	99	99	126	1.00	.79
2BOO	241	398	490	.61	.50

TABLE 4. - HALF-LIFE CYCLE STRAINRANGE VALUES AND CORRESPONDING DAMAGE FRACTIONS FOR MPC TESTS

Test bar	Number of interspersed fatigue cycles	Observed life cycles	Predicted life cycles	Strainrange components percent			Damage fractions (summation =1.000)		
				Interspersion	Creep period		Interspersion	Creep period	
				PP	PP	CP	PP damage	PP damage	CP damage
2A4B	1	59	57	1.99	0.115	2.570	0.164	0.014	0.822
2A1A	1	141	160	1.23	.113	1.451	.197	.020	.783
2A2B	2	73	122	1.94	.490	1.070	.670	.009	.321
2A3AA	5	96	99	1.23	.082	1.290	.612	.007	.381
2A6BB	11	39	30	1.96	.070	1.076	.916	.003	.081
2A5AA	22	29	34	1.20	.095	1.920	.885	.001	.114
2A4E	1	67	68	0.28	.049	2.610	.006	.007	.987
2B1A	1	202	408	1.23	.027	0.716	.505	.006	.489
2B3A	5	92	153	1.21	.037	0.454	.919	.003	.078
2AOO	--	99	126	----	.089	1.875	-----	.015	.985
2BOO	--	241	490	----	.051	0.924	-----	.021	.979

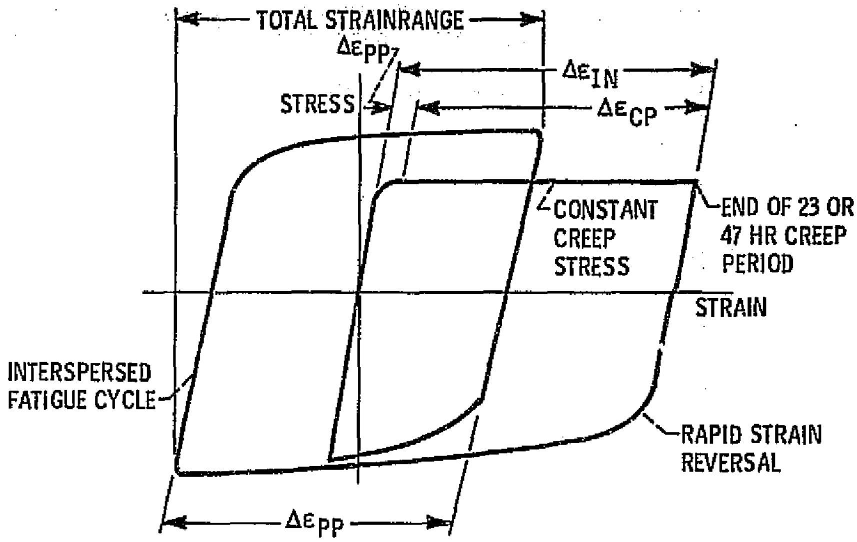

Fig. 1. - Schematic hysteresis loops associated with MPC creep-fatigue interspersion tests (16). Cyclic creep rupture tests involve only creep portion with no interspersed fatigue cycles. Partitioned strainranges indicated on loops.

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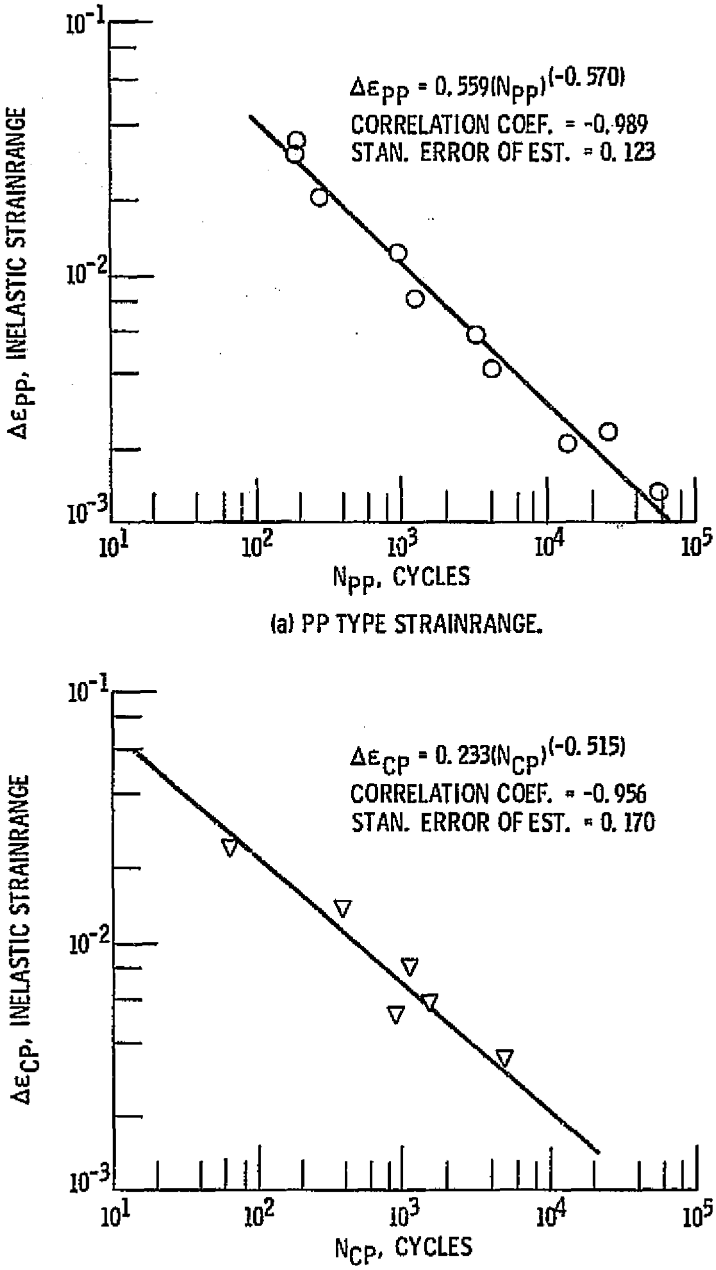

(a) PP TYPE STRAINRANGE.

(b) CP TYPE STRAINRANGE.

Fig. 2. - Partitioned strainrange-life relations for annealed $2\frac{1}{4}$Cr-1Mo steel.

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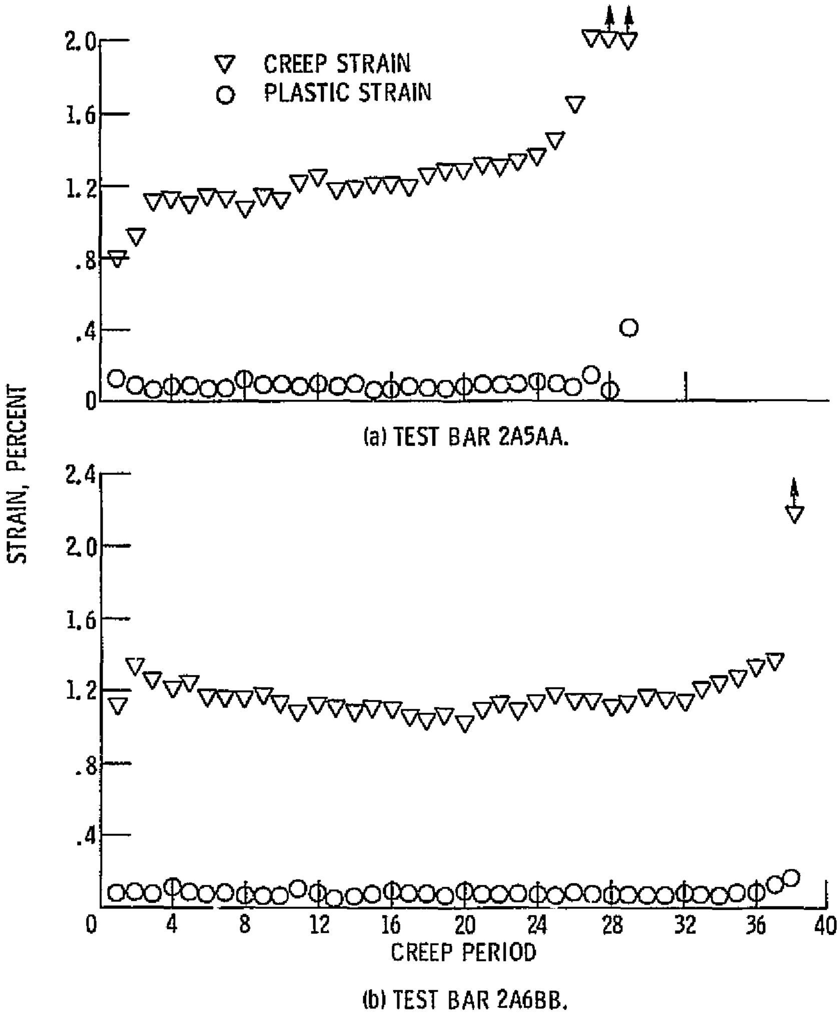

Fig. 3. - Strains accumulated at end of each creep period during MPC creep-fatigue interspersion tests of annealed $2\frac{1}{4}$Cr-1Mo steel at 1000° F (538° C).

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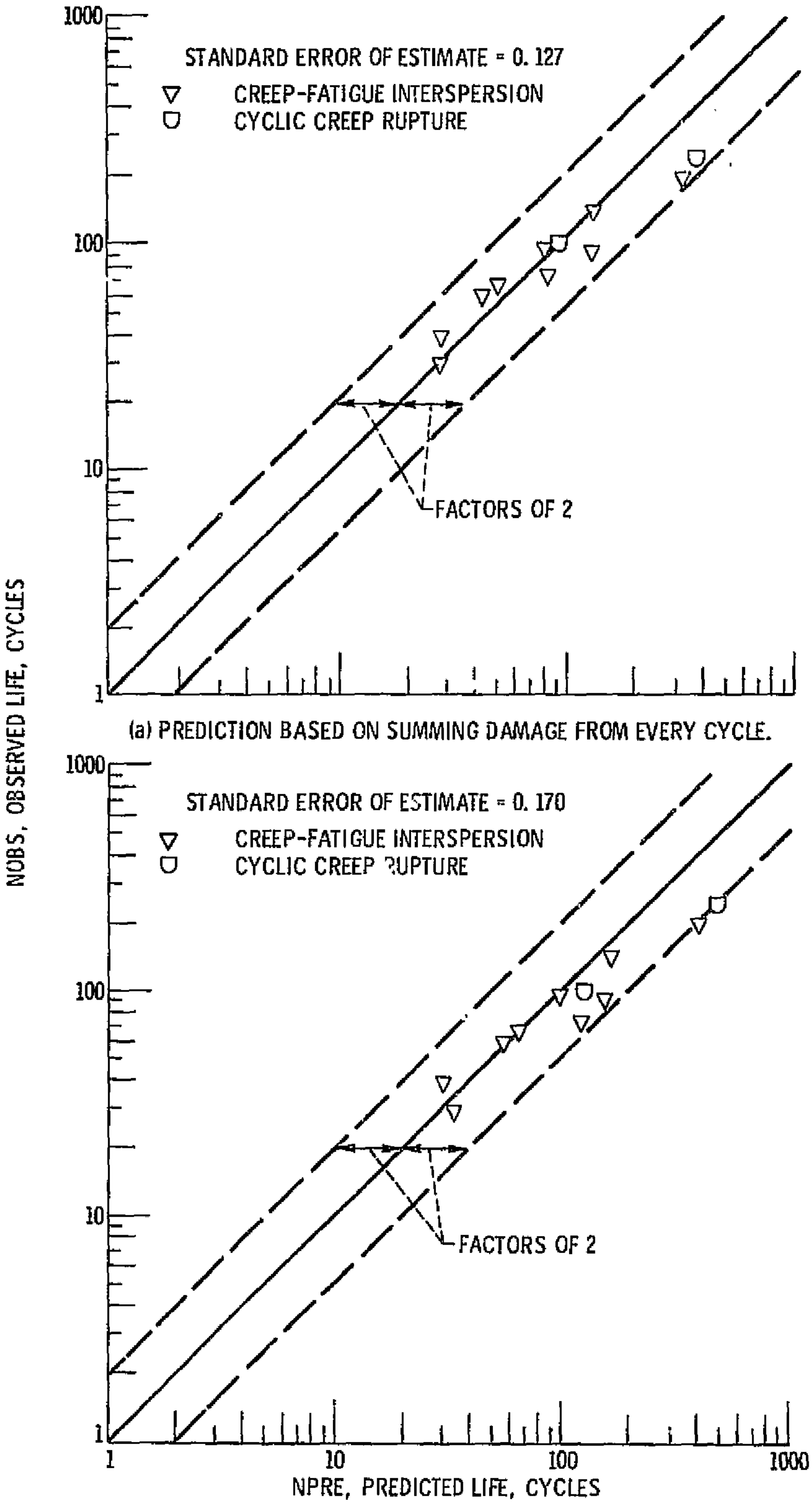

(a) PREDICTION BASED ON SUMMING DAMAGE FROM EVERY CYCLE.

(b) PREDICTIONS BASED ON DAMAGE DONE ON HALF-LIFE CYCLE.

Fig. 4. - Comparison of observed MPC creep-fatigue lives of annealed $2\frac{1}{4}$Cr-1Mo steel versus lives predicted on basis of strainrange partitioning using interaction damage rule.

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